State of the Art SRF Cavity Performance

Lutz Lilje@desy.de
DESY
LINAC 2004

• SRF features
• State-of the-art beta=1 cavities
• Projects and new challenges
Thank You...

• ... to the colleagues from the TESLA collaboration

• ... to the colleagues in the field of superconducting RF cavities for the material provided esp. P. Kneisel, J. Sekutowicz, G. Hoffstätter, M Kelly, H. Padamsee.
Surface Resistance $R_s(T)$

Geometry factor:

$$Q_0 = \frac{G}{R_s}$$

$G = 270$ Ohm

Surface resistance:

$$R_s = \frac{A}{T} \omega^2 e^{-\frac{\Delta}{k_B T_C} \frac{T_C}{T}} + R_{res}$$

Typical Quality factor:

$Q_0 > 1 \times 10^{10}$ at 2K

$700$ nOhm @ 4.2K

$<10$ nOhm @ 2K
Superconducting Cavities

- SC cavities offer
  - a surface resistance which is six orders of magnitude lower than normal conductors (NC)
  - high efficiency, even when cooling is included
    - large currents can be accelerated
    - high duty cycle up to continuous wave (cw) operation
  - low frequency, large aperture
  - high accelerating gradients
    - Theoretical limit for the TESLA shape is between 45-50 MV/m
  - energy recovery
  - attractive for a wide range of projects....
Accelerator Projects Featuring SRF Cavities

- **Disclaimer**: Focus of this talk is mostly on electron machines with beta = 1
  - for beta < 1 see J. Delayen TH301

- **LINACs**
  - TESLA, European XFEL, TTF, ELBE, BESSY-FEL, MIT Bates, FERMILAB 8 GeV, SNS

- **Recirculating LINACS**
  - S-DALINAC, CEBAF, LUX, Arc-en-Ciel, Neutrino Factory/Muon Collider

- **ERLs**
  - JLAB FEL, JAERI, Cornell FEL, PERL (BNL), 4GLS, KEK-ERL, RHIC-II

- **Storage rings**
  - HEP
    - KEK-B, CESR, HERA, Tristan, LEP
  - Synchrotron Light
    - SOLEIL, CHESS, Canadian Light Source, Taiwan Light Source, DIAMOND

---

No guarantee for completeness...
New Applications for SRF Cavities

- high energy physics and synchrotron radiation physics (chemistry, biology...) have taken profit of this technology already since a long time

- technology is well advanced and available
  - the small surface resistance of the superconducting necessitates avoidance of NC contaminations larger than a few µm
  - detailed material specification and quality control are done
  - tight specification for fabrication e.g. welds have been implemented
  - clean room technology is a must

- new projects are aiming at
  - high gradient (e.g. TESLA)
    - further improvement of the surface preparation
  - increasing electron currents (ERLs)
    - Higher-Order-Mode (HOM) damping
  - high duty cycle (CW FELs)
Storage Ring Light Sources

H. Padamsee, PAC2001

Diamond Site

SRRC Taiwan

Canadian Light Source
Example: Standard SC Technology

- Cornell 500 MHz system
  - developed by Cornell University
  - commercially available
  - used in:
    - Canadian light source
    - NSRRC (Taiwan light source)
    - DIAMOND (UK)
  - see EPAC 04: MOPLT041, MOPLT040
- Overview on magnetic peak field over a wide frequency range
Magnetic Peak Surface Fields Today and 1980

Today

1980

B_{peak} [mT]

Frequency [Hz]

Lutz Lilje  DESY  08.03.2005
Recent Developments and Challenges

- Surface preparation improvement
- CW modules
- Superstructures
- New elliptical cavity shapes
- CW ERL
Surface Preparation: Electropolishing

- Electropolishing (EP) of niobium surfaces is a key technology to achieve the highest electrical and magnetic surface fields.
- KEK/ Nomura Plating pioneered application of EP to elliptical niobium cavities since TRISTAN using a Siemens’ recipe.
- EP has also been successfully applied to
  - Low-Beta Quarter wave structures
  - TESLA nine-cells
Electropolishing Offers Improved Surface Quality

Conventional Etch (BCP) vs. EP
Electropolished 1.3 GHz Elliptical Niobium Cavities

K. Saito et al. KEK 1998/1999

Test temperature: 1.6 K

One-cell cavities

Eacc [MV/m]

K-14: half cell annealed at 1400°C, EP
K-8: BP, 760°C annealed. EP
K-9: BP, 760°C annealed, EP
JL-1: fabricated at CEBAF, CP, EP
K-11: CP, 760°C annealed, EP
K-22: CP, EP

08.03.2005 Lutz Lilje DESY
4.2 K Residual resistivity – 80-100 MHz
Quarter-wave structures

Ken Shepherd, SRF 2003, Lübeck
Note the different test temperature in this low power performance test: 1.6 K – 2K
Comparison of EP to Standard Etch  
(Results from the KEK-DESY Collaboration)

- EP offers systematically higher gradient than standard etch (single cell results from mode analysis of multi-cells)

After Standard etch Average  
28.9 +/- 1.1 MV/m

After EP Average  
35.6 +/- 2.3 MV/m

<table>
<thead>
<tr>
<th>$E_{acc}$ [MV/m]</th>
<th>Number of cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>5</td>
</tr>
<tr>
<td>30</td>
<td>20</td>
</tr>
<tr>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
</tr>
</tbody>
</table>

Lutz Lilje  DESY
08.03.2005
High power tests give Cavity-Coupler-wise the full information about the system’s behaviour e.g. it corresponds to 1/8th of an accelerator module.

Longterm test:
- No breakdown in 1100 hours at 35 MV/m (neither the Cavity nor the Coupler)
- No degradation was observed when breakdowns were forced (thermal quenches and coupler breakdowns)
High Power Test Results

- One cavity without post-purification achieved a gradient of more than 35 MV/m with a $Q_0$ of $10^{10}$. This is about a factor of 2 above the TESLA specification.
One of the electropolished cavities (AC72) was installed into an accelerating module for the VUV-FEL.

Very low cryogenic losses as in high power tests.

Standard X-ray radiation measurement indicates no radiation up to 35 MV/m.
From Pulsed to Continuous-Wave (CW)

• TESLA is a pulsed machine
  – large heat losses due to high gradient
  – gradient is the major research issue

• for CW operation
  – high quality factor at intermediate gradients is crucial
  – ultimate dream is $Q_0 \gg 10^{10}$ at 15 MV/m

• often this means the same thing:
  – avoid field emission
  – good niobium quality i.e. eddy-current scanned material
  – detailed welding specification
stable CW operation at 15 MV/m achieved at JLAB-FEL
  – etched cavities
  – no postpurification using titanium furnace treatment
most of the operation at lower gradient by user request so far, but not limited by the cavities
Recent Developments and Challenges

- Surface preparation improvement
- CW modules
- Superstructures
- New elliptical cavity shapes
- CW ERL
Superstructures

- more economical (e.g. less high power couplers)
- higher fill factor of the accelerator
- improved HOM damping
- demonstrated that
  - energy refilling does work even with weakly coupled sub-units

J. Sekutowicz, SRF2003, Lübeck
Superstructure Layout

- Cell-to-cell coupling: \(\sim 2\%\)
- Structure-to-structure: \(\sim 0.04\%\)
- Compare standard nine-cell with superstructure:
2x7-cell Superstructure Prototypes at TTF
Energy Transfer

- Measured: \( \Delta \frac{E}{E} \) (rms) \( \leq 2 \cdot 10^{-4} \)
- TESLA-Specification: \( \Delta \frac{E}{E} \) (rms) \( \leq 5 \cdot 10^{-4} \)
HOMs

- damping of dipoles with \((R/Q) \geq 1 \, \Omega/cm^2\) which are relevant for the TESLA beam was by factor 5÷100 better than spec.

**Beam Dynamics limit** \(Q_{\text{ext}} \leq 10^5\)
Recent Developments and Challenges

- Surface preparation improvement
- CW modules
- Superstructures
- New elliptical cavity shapes
- CW ERL
New Elliptical Cavity Shapes

- Example: CEBAF upgrade
  - high-gradient operation (HG):
    - lower $E_{surf}$
    - reduce field emission
  - low-loss (LL)
    - maximize shunt impedance and geometric factor
    - with a given cryo power
      maximise achievable gradient

<table>
<thead>
<tr>
<th>Parameter</th>
<th>OC</th>
<th>HG</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{equator}$ [mm]</td>
<td>187.0</td>
<td>180.5</td>
<td>174.0</td>
</tr>
<tr>
<td>$\phi_{iris}$   [mm]</td>
<td>70.0</td>
<td>61.4</td>
<td>53.0</td>
</tr>
<tr>
<td>$k_{cc}^*$       [%]</td>
<td>3.29</td>
<td>1.72</td>
<td>1.49</td>
</tr>
<tr>
<td>$E_{peak}/E_{acc}$ [-]</td>
<td>2.56</td>
<td>1.89</td>
<td>2.17</td>
</tr>
<tr>
<td>$B_{peak}/E_{acc}$ [mT/(MV/m)]</td>
<td>4.56</td>
<td>4.26</td>
<td>3.74</td>
</tr>
<tr>
<td>$R/Q$            [$\Omega$]</td>
<td>96.5</td>
<td>111.9</td>
<td>128.8</td>
</tr>
<tr>
<td>$G$              [$\Omega$]</td>
<td>273.8</td>
<td>265.5</td>
<td>280.3</td>
</tr>
<tr>
<td>$R/Q\cdot G$    [$\Omega \cdot \Omega$]</td>
<td>26422</td>
<td>29709</td>
<td>36103</td>
</tr>
</tbody>
</table>
New Elliptical Cavity Shapes (ctd.)

- multipacting-free
- multi-cells show $E_{\text{acc}} \approx 20$ MV/m
- one-cell of the low loss variety gives an $E_{\text{surf}}$ of 87 MV/m
- HOMs
  - damping of niobium prototypes confirms calculations and copper model measurements,
  - improved feedthroughs with better thermal design under fabrication
Recent Developments and Challenges

- Surface preparation improvement
- CW modules
- Superstructures
- New elliptical cavity shapes
- CW ERL
CW ERLs

- Promises:
  - high efficiency
  - lower RF power requirements
    - nearly independent of accelerated current
    - need to compensate wall losses, therefore superconductivity
  - linac-like beam quality
  - beam power at the dump reduced

- Examples
  - existing: JLAB, JAERI
    - ~10 mA
  - proposed: Cornell ERL Prototype
    - ~100 mA

- Challenges
  - higher order mode damping
  - high cw power couplers
Example: Cornell ERL Prototype Cavities

- **Injector**
  - two-cells (‘HOM-free’)
  - Ferrite broadband absorbers at 80 K
  - 130 kW CW coupler

- **Linac**
  - seven-cells
  - LLRF stability
    - Phase 0.06 degrees
    - Amplitude: $3 \times 10^4$
  - $Q_{ext} = 2.6 \times 10^7$ (microphonics)
  - 140 W losses per cavity from beam-excited monopole modes
  - opposite HOM couplers to reduce transverse kicks
  - enlarged beam tube
  - 6 HOM loop couplers:
    - reduce power per coupler
    - damp quadrupole modes reliable.
  - ferrite broadband absorbers at 80 K
Summary

- SC cavities are a standard tool becoming more and more interesting for several applications
  - CW linacs (e.g. FELs, ERLs)
  - high gradient applications (e.g. TESLA)
- this is due to:
  - surface preparation provides high gradients near the theoretical limit
    - a big variety cavities achieve $B_{\text{surf}} = 100\text{mT}$ easily
    - with EP up to 150 mT in multi-cells
    - even higher Q0 at intermediate gradients is desirable for cw applications
  - new cavity design options
    - cell shape
    - superstructures
  - improved HOM damping concepts allow to increase currents